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Search for Technicolor with Delphi

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Abstract

Technicolor represents a viable alternative to the Higgs mechanism to generate the W/Z masses. While the minimal version of the model seems rejected by LEP1 precision measurements, one cannot exclude more elaborated schemes like "walking-technicolor" which predict a rich spectrum of mesons which could be directly/indirectly observed at LEP2. This note presents the preliminary results of the search for technicolor with the DELPHI detector at LEP based on $W_L^+\pi_T^-$ and $\pi_T^+\pi_T^-$ final states.

1 Introduction

In spite of outstanding theoretical and experimental achievements, particle physics has not been able to reach a conclusion on the simple question: from which mechanism does mass originate? It is a common belief that such a mechanism will be characterised by the observation of at least a scalar particle. Whether this object is elementary (SM or MSSM scenario), composite (technicolor scenario), or too heavy to be observed as a particle remains uncertain.

In this note the framework of technicolor will be briefly recalled and the possible signals which can be observed at LEP2 will be reviewed. In section 4 the constraints on the technicolor model obtained for $M_{\rho_T} < \sqrt{s}$ will be discussed while in section 5 the direct searches of technipions performed with the Delphi detector using the data collected in 1999 will be described.

2 Data Sample

The detailed description of the DELPHI detector can be found elsewhere[1]. For the search for π_T production, the statistics of DELPHI taken in 1999 for $\sqrt{s}$ between 192 and 202 GeV are used. The integrated luminosity is 25.8 pb^{-1} for $\sqrt{s}$ = 192 GeV, 76.9 pb^{-1} for $\sqrt{s}$ = 196 GeV, 84.3 pb^{-1} for $\sqrt{s}$ = 200 GeV and 41.1 pb^{-1} for $\sqrt{s}$ = 202 GeV. In the search for ρ_T below 202 GeV, the statistics at $\sqrt{s}$ = 161 GeV (10 pb^{-1}), 172 GeV (10 pb^{-1}), 183 GeV (54 pb^{-1}) and 189 GeV (158 pb^{-1}) are also used.

Simulated events were produced with the DELPHI simulation program DELSIM and were passed through the same reconstruction chain as the data. For the simulation of 4-fermion final states the generator EXCALIBUR[2] was used, while the background process $e^+e^- \rightarrow q\bar{q}(+n\gamma)$ was simulated using PYTHIA[3]. For the simulation of two-photon interactions the program TWOGAM[4] was used.

3 The Technicolor scheme at LEP

Technicolor provides an elegant scheme to generate W/Z masses. These bosons can be seen as condensates of a new family of quarks (the techniquarks) which obey a QCD-like interaction with an effective scale Λ_{TC} much larger than Λ_{QCD}. It also predicts heavy (> 1 TeV) vector mesons which can't be observed at LEP2.

As well known, this scheme encounters several problems. It can't correctly generate fermion masses and, in its simplest version, it contradicts the LEP1 precision measurements since it gives positive contributions to the S parameter[5].

Extensions[6] have been worked out which allow to solve these problems at the price of losing prediction power. These schemes depart from the straightforward analogy with QCD, with the usual asymptotic freedom behaviour. It turns out instead that perturbative calculations do not work ("walking technicolor"), and therefore the theory cannot be fully tested by precision measurements.

These extensions call for a large number N_D of technidoublets [7] and therefore additional scalar (π_T, π'_T) and vector (ρ_T, ω_T) mesons, which can be light enough to be observed at LEP2 or Tevatron. The CDF experiment at the Tevatron[8] and the L3 collaboration at LEP[9] have already published preliminary limits reaching about 200 GeV for the ρ_T mass.

As discussed in the following sections, clear TC signals can be expected at LEP2 allowing a full coverage of a scenario with $M_{\rho_T} < \sqrt{s}$. In addition one could observe technipions up to a mass $\sim \sqrt{s}/2$ even if M_{ρ_T} is assumed very heavy.

For the description of ρ_T production the theoretical model given in [10] is used. In this paper only the production of $\rho_T^{(*)} \to W_L\pi_T$, $\pi_T\pi_T$ and $\rho_T \to f_i\bar{f}_i$, W_LW_L is considered. The final state $W_T\pi_T$ (where W_T stands for the transversely polarised W-boson) can also be produced through $e^+e^- \to \rho_T, \omega_T \to W_T\pi_T$. It does not interfere with $W_L\pi_T$ and gives a supplementary contribution to the $W\pi_T$ cross section[10]. It depends, however, on additional free parameters and is not taken into account in this note. In this sense the limits obtained on technicolor production are conservative.

4 Search for ρ_T below $\sqrt{s}$

This section dicusses a scenario with $M_{\rho_T} < \sqrt{s}$, implying that ρ_T can be produced on mass-shell through radiative return.

Below the W pair threshold, assuming that the $\pi_T^+\pi_T^-$ and $W_L^+\pi_T^-$ channels are kinematically closed and the $\pi_T^0\gamma$ channel is suppressed, the ρ_T resonance is very narrow, of the order of a few 10 MeV, and decays to an $f_i\bar{f}_i$ pair. If it has a mass below the centre of mass energy, initial state radiation will allow it to be observed in the standard $\sqrt{s'}$ distribution as a narrow peak. The rate is approximately given by the following formula :

$$R_{\rho_T} \sim ln(s/m_e^2)\frac{\Gamma_{\rho_T}^{e^+e^-}/M_{\rho_T}}{\Gamma_Z^{e^+e^-}/M_Z}\frac{1}{1 - M_{\rho_T}^2/s}$$

where R_{ρ_T} is the radiative return cross section normalised to the point-like cross section. The simplest possibility is to observe this peak in $e^+e^- \to \mu^+\mu^-\gamma$, although it should also be seen in $e^+e^- \to q\bar{q}\gamma$. Using the formulae from [10] one can derive the numbers for the cross section and branching ratio of $\rho_T \to \mu^+\mu^-$ given in table 1. The numbers of events from the standard sources and from the expected ρ_T contribution are given for a 1 GeV window for each mass of ρ_t and derived taking into account the reconstruction efficiency and expected mass resolution. Figure 1 shows the expected and observed mass spectra of $\mu^+\mu^-$ from the preliminary analysis of $\mu^+\mu^-(+n\gamma)$ events obtained for all available statistics at $\sqrt{s} > 160$ GeV/c^2. It can be concluded from this figure and table 1, that a signal from ρ_T should be visible for all ρ_T masses above the Z^0 pole, and therefore its production is excluded in all cases when the main decay mode of ρ_T is $\rho_T \to f_i\bar{f}_i$.

If $2M_W < M_{\rho_T} <$200 GeV, and if the $\pi_T^+\pi_T^-$ and $W_L^+\pi_T^-$ channels are still closed, one can still produce ρ_T on mass shell by radiative return, and ρ_T will decay into W^+W^- unless the mixing angle between W_L and π_T is very small. In the latter case, the constraint obtained from the $\sqrt{s'}$ distribution in the $\mu^+\mu^-$ channel operates up to the highest available energy: e.g. a ρ_t with 190 GeV/c^2 mass would give an excess of 33 $\mu^+\mu^-$ events for $\sqrt{s} > 199$ GeV in the bin of 1 GeV, while only 3 events are observed in data and 2.6 are expected. If BR($\rho_T \to W^+W^-$) is dominant, one finds that the technicolor contribution would produce an excess with respect to the Standard Model W^+W^- pair production. This

M_{ρ_T} GeV	σ_{ρ_T} pb ($\sqrt{s}=202GeV$)	BR($\rho_T \to \mu^+\mu^-$)	N($\rho_T \to \mu^+\mu^-$)	N(MC)	N(data)
190	5.5	0	–	–	–
170	2.3	0	–	–	–
150	1.6	0.10	36	2.8	5
130	1.4	0.09	30	2.6	1
110	1.8	0.08	43	3.1	5

Table 1: Expected cross-sections of radiative return ρ_T production, the numbers of events from $\rho_T \to \mu^+\mu^-$, and the numbers expected from the standard sources N(MC) and observed in data N(data) per 1 GeV for the full DELPHI statistics with $\sqrt{s} > 160GeV$. For masses of ρ_T exceeding $2M_W$ it is supposed that the channels $\rho_T \to W^+W^-$, $W\pi_T$ or $\pi_T\pi_T$ dominate. It is also supposed that the decay $\rho_T \to \pi_T^0\gamma$ is suppressed.

excess would distort the energy dependence of W^+W^- cross section, producing excess above 3 pb which is clearly excluded by our data[11].

If ρ_T can decay into $\pi_T^+\pi_T^-$ or $W_L^+\pi_T^-$, these modes become dominant. The cross-sections given in table 1 remain the same, and therefore one can observe a huge signal using the direct search for technicolor described in the next section, provided that events with initial state radiation are not removed. As will be shown in the next section, the limit obtained on the contribution of $\pi_T^+\pi_T^-$ and $W_L^+\pi_T^-$ at 95% C.L. is of the order of 0.2 pb. Comparing this with the radiative return cross section values from table 1 one can conclude that this possibility is excluded by our data for all masses of ρ_T below $\sqrt{s}$.

Summarising this section, it can be concluded that the production of ρ_T is excluded by DELPHI data up to the highest available energy for all possible decay patterns of ρ_T.

5 Search for π_T

5.1 Production of $W_L^+\pi_T^-$ and $\pi_T^+\pi_T^-$ final states

If π_T is light enough, it becomes possible to produce $W_L^+\pi_T^-$ or even $\pi_T^+\pi_T^-$ final states which can provide striking signatures. The reason for this is that technipions are expected[12] to decay into the heaviest fermions. Charged technipions therefore prefer final states with b quark, which can be separated from the W bosons applying b-tagging. In this analysis the production of b quark is assumed in ~90% of π_T decays, other important modes are $\pi_T^- \to s\bar{c}$ and $\tau\bar{\nu}_\tau$ [10, 13]. See however the appendix for the discussion of the possibility of a W-like decay pattern of the π_T.

The cross section of technipion production normalised to the point-like cross section is[12]:

$$R_{\rho_T \to a^+b^-} = \frac{[|A_{eL}(s)|^2 + |A_{eR}(s)|^2]C_{ab}\lambda^{3/2}}{8(1-s/M_{\rho_T}^2)^2} \tag{1}$$

where C_{ab}=$\cos^4\chi$ for $\pi_T^+\pi_T^-$, $2\cos^2\chi\sin^2\chi$ for $W_L^+\pi_T^-$ and $\sin^4\chi$ for $W_L^+W_L^-$ with $\sin^2\chi$=1/N$_D$. The $A_{eL,R}(s)$ can be found in [10], for convenience their definition is given in appendix. The phase space suppression factor is:

$$\lambda = (1 - m_a^2/s - m_b^2/s)^2 - 4m_a^2m_b^2/s^2$$

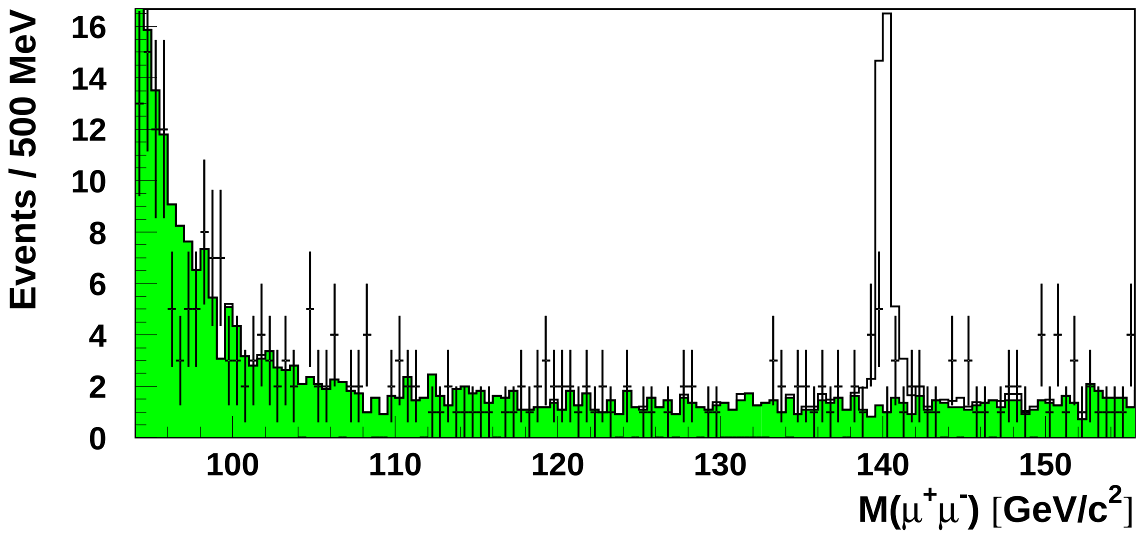

Figure 1: Distribution of the mass of $\mu^+\mu^-$ system in $e^+e^- \to \mu^+\mu^-(+n\gamma)$. The points are the data, the filled histogram is the simulation prediction. The possible contribution of $\rho_T \to \mu^+\mu^-$ with $M_{\rho_T} = 140$ GeV/c^2 is also shown.

These processes depend on 3 quantities : M_{π_T}, M_{ρ_T} and N$_D$.

Note that for a highly virtual ρ_T contribution, even for $M^2_{\rho_T} \to \infty$, the value of $R_{\rho_T \to a^+b^-}$ remains finite. If one ignores the Z contributions, expressions given in the appendix lead to $R_{\rho_T \to a^+b^-} \sim C_{ab}/4$, as expected for a point-like coupling of a photon to $\pi_T^+\pi_T^-$. This correct behaviour results from our choice of the ρ propagator. This feature is noticeable since it allows LEP2 to be sensitive to light π_T even for a very heavy ρ_T.

5.2 Analysis Procedure

In this note only the search for the technicolor production in the four-jet final state is described. The analysis starts with the four-jet preselection described in [14]. This aimes to eliminate the radiative and $\gamma\gamma$ events and to reduce the QCD and Z$^0\gamma^*$ background, it has also been used in the HZ and hA analyses in the four-jet channels. It should be noted that radiative return events with photon energy less than 30 GeV are not rejected by this preselection. This makes the analysis sensitive to the radiative return production of ρ_T with $M_{\rho_T} < \sqrt{s}$. In addition to the preselection of [14], the parameter of the DURHAM algorithm y_{34} was required to exceed 0.003. The resulting numbers of expected events and the signal efficiencies are given in Table 2.

To reduce the QCD background, different shape variables were investigated. The sum of the second and fourth Fox-Wolfram moments, $H_2 + H_4$, was chosen, as it proved to be able to reduce this background substantially while maintaining the efficiency of both 4 jet channels $\pi_T\pi_T$ and $W\pi_T$ at a reasonable level. Events were required to have $H_2+H_4 \leq 0.6$. The agreement between data and background simulation of this variable after the cut on y_{34} is shown in Figure 2.

Events originating from the signal have one or two b-quarks in the final state while the main background from W^+W^- contains very few b-quarks. Therefore, to reduce the contribution of W pairs, the b-tagging procedure [15] was applied. Figure 3 shows the distribution of the b-tagging variable for data and simulation. Agreement between data and simulation is good in the full range of this variable. The non-normalised contribution of $\pi_T\pi_T$ channel, also shown in this figure, would give the excess of events at high values of b-tagging variable.

It was found that a cut on the b-tagging variable at 1 maximises the sensitivity for the $\pi_T\pi_T$ channel and is almost optimal for the $W\pi_T$. Therefore this cut is used to search for the technicolor signal.

After this cut 58 events are observed in data and 53 events are expected from the simulation. The contribution of the different background sources together with the selection efficiencies of the $\pi_T\pi_T$ and $W_L\pi_T$ channels can be found in table 2. Table 3 gives the selection efficiencies of technicolor production for different masses of π_T.

To construct the mass estimator for the possible technicolor contribution, all selected events were forced to four jets using the DURHAM clustering algorithm, and a 5 constraint fit requiring the conservation of energy and momentum and equal masses of opposite pairs of jets was applied to all possible pairings of jets. The combination with the minimal χ^2 of the 5C fit was selected. The mass distribution obtained using this estimator for all selected events is shown in Figure 4. The possible contribution of $\pi_T\pi_T$ production with M_{π_T} = 89 GeV/c^2, also shown in this figure, would be seen as the narrow peak. The channel $W_L\pi_T$ would give a slightly wider peak shifted towards the mass of the W. The form of the mass spectrum of the sum of these two channels depends on the ρ_t mass and the mixing angle χ.

The sensitivity of this analysis to technicolor production varies between 0.2 and 0.3 pb for π_T masses between 60 and 100 GeV/c^2.

Selection	Data	Total background	$q\bar{q}(\gamma)$	4 fermion	Efficiency $\pi_T\pi_T$ (%)	Efficiency $W_L\pi_T$ (%)
Preselection	2465	2434.3	753.3	1681	85.7	60.0
$y_{34} \geq 0.003$	2045	1998.5	452	1546.5	82.8	56.2
$H_2 + H_4 \leq 0.6$	1443	1455.6	174.5	1281.1	72	47.7
xeffz0$\geq$ 1	58	53	20.4	32.6	41.5	14.9

Table 2: Effect of the selection cuts on data, simulated background and simulated signal events at $\sqrt{s}$ = 192-202 GeV. Efficiencies are given for M_{π_T} = 89 GeV/c^2 and include the topolgical branching ratios of W and π_T to two jets.

5.3 Results

No significant contribution of technicolor production is observed either in the total number of selected events or in the mass spectrum of Figure 4. Therefore the results of our analysis

channel	$M_{\pi_T} = 69$ GeV/c^2	$M_{\pi_T} = 79$ GeV/c^2	$M_{\pi_T} = 89$ GeV/c^2
$W_L \pi_T$	0.12	0.13	0.15
$\pi_T \pi_T$	0.30	0.37	0.42

Table 3: Selection efficiency (including topological branching rates) for $W_L \pi_T$ and $\pi_T \pi_T$ for different masses of M_{π_T}.

are used to set limits on technicolor production. The 95% C.L. exclusion region in the (M_{ρ_T}, M_{π_T}) plane is shown as the filled area in Figure 5. It is valid for any possible mixing angle χ. The exclusion curves for two particular values of mixing corresponding to $N_D = 2$ (maximal mixing) and $N_D = 9$ (theoretically preferred[10]), are also shown.

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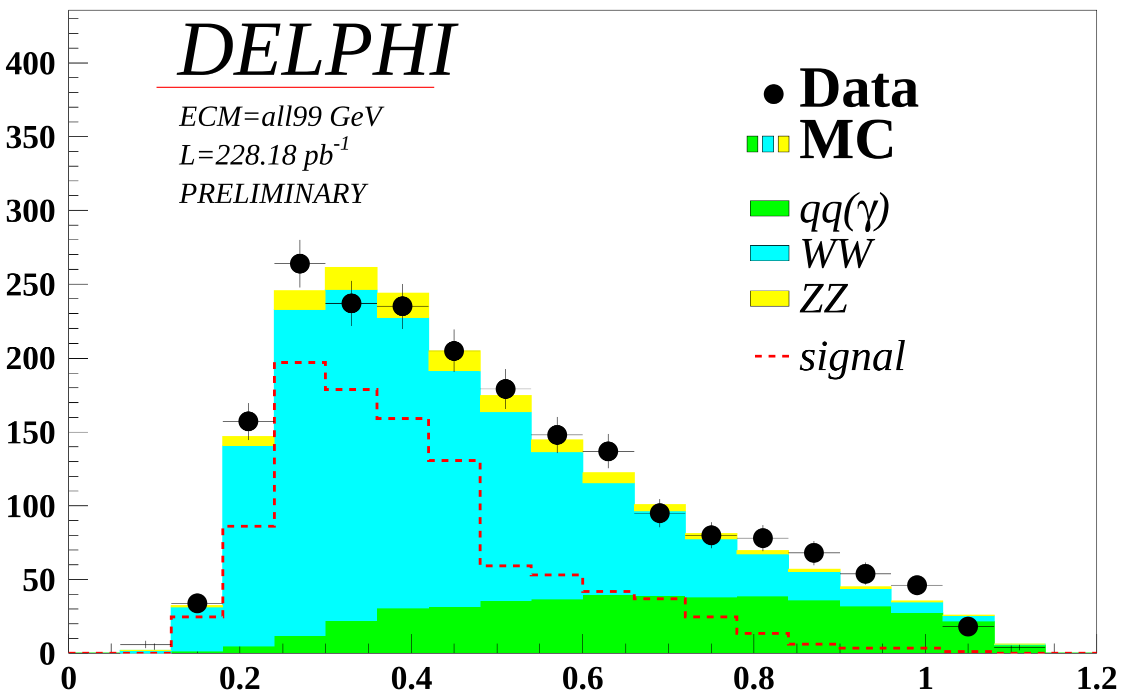

Figure 2: Distributions of the $H_2 + H_4$ variable after preselection and $y_{34} \geq 0.003$ cut. Normalisation of the technicolor signal with $M_{\pi_T} = 89$ GeV/c^2 (dashed histogram) is arbitrary.

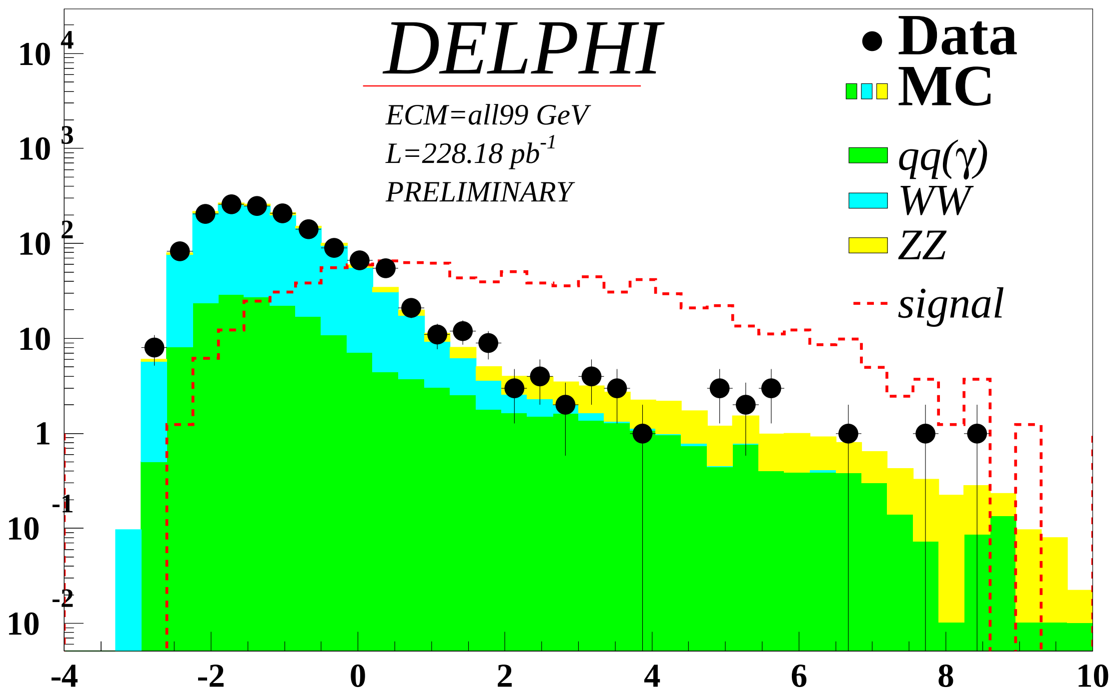

Figure 3: Distributions of the combined b-tag variable after the $H_2 + H_4$ cut. Normalisation of the technicolor signal with $M_{\pi_T} = 89$ GeV$/c^2$ (dashed histogram) is arbitrary.

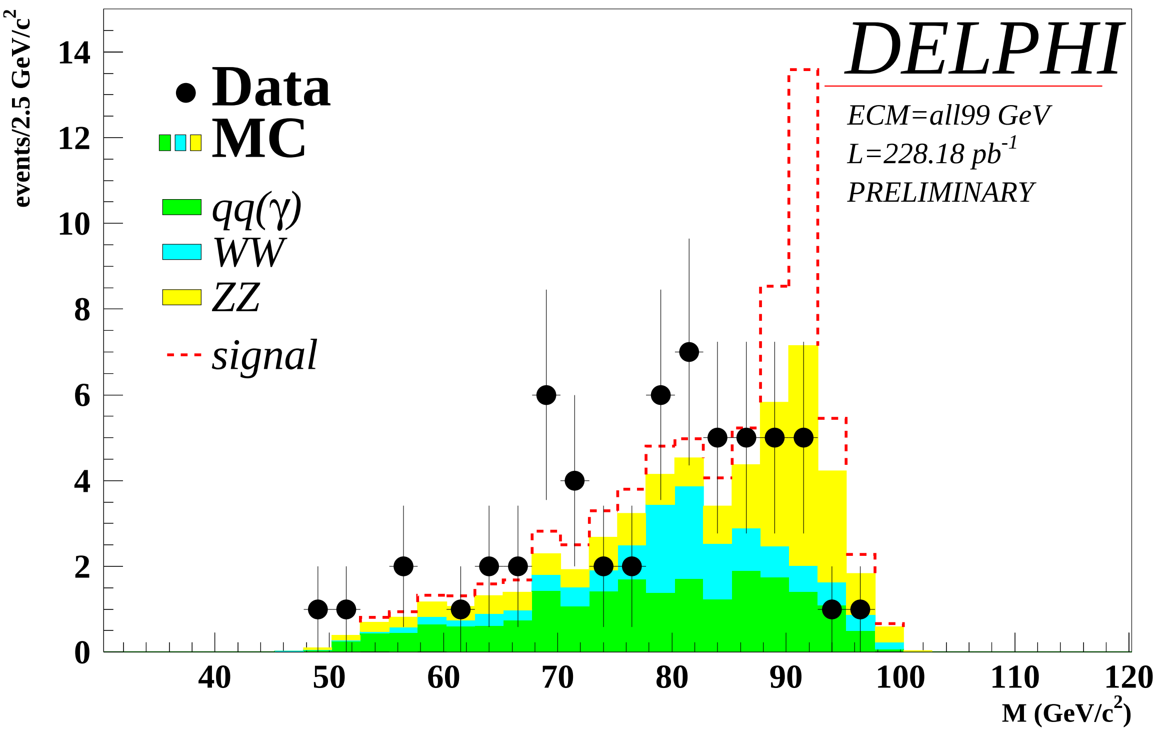

Figure 4: Mass distributions at the end of the analysis. Normalisation of the technicolor signal with $M_{\pi_T} = 89\ \mathrm{GeV}/c^2$ (dashed histogram) is arbitrary.

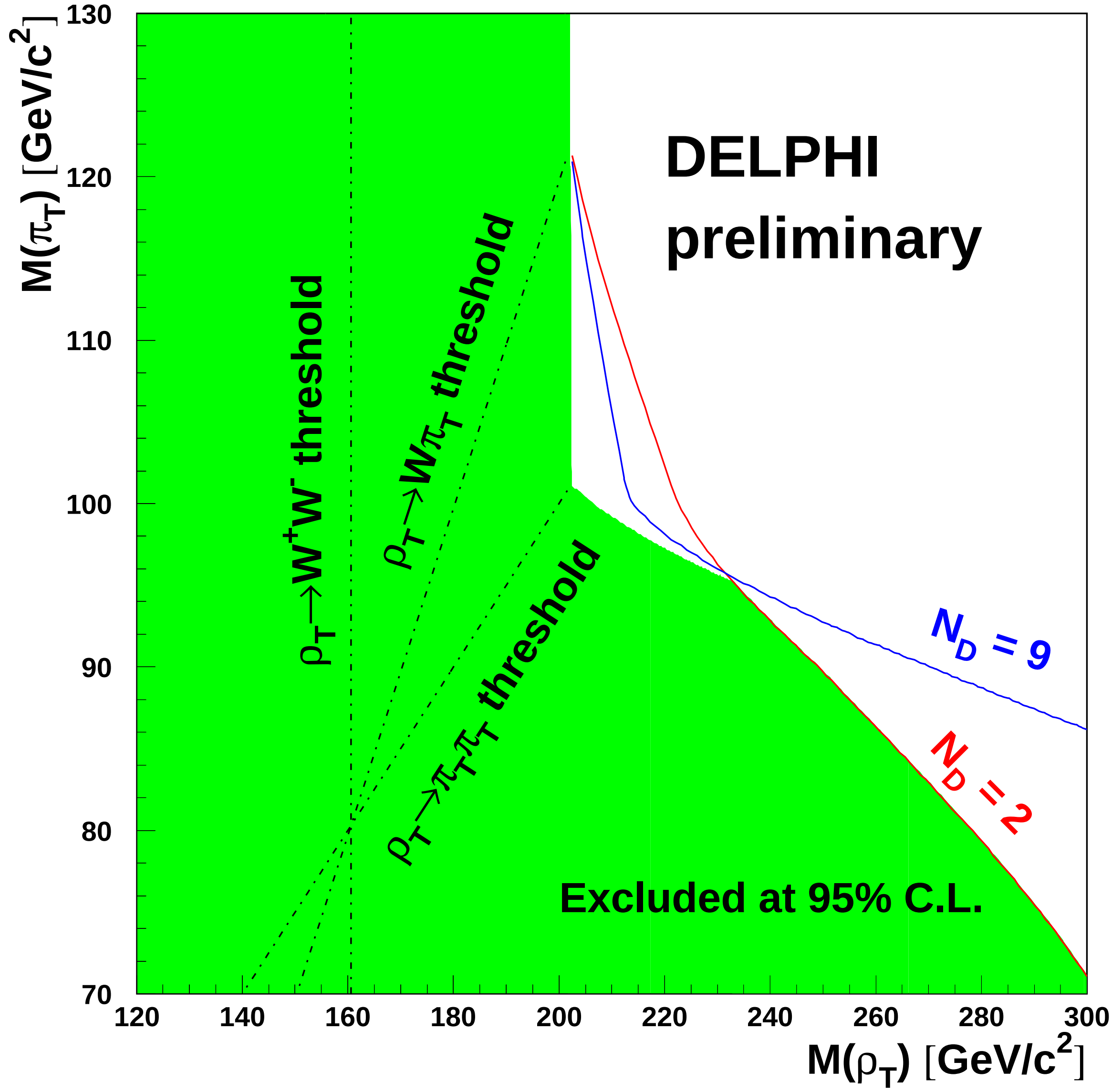

Figure 5: The region in $(M_{\rho_T} - M_{\pi_T})$ plane (filled area) excluded at 95% C.L. for any value of W_L - π_T mixing.

Appendix

Coupling of technivector mesons to fermions

One has[12]:

$$\Gamma(\rho_T^0 \to \bar{f}_i f_i) = \frac{N_f \alpha^2}{3\alpha_{\rho_T}} \frac{p_i(s+2m_i^2)}{s} A_i^0(s)$$

where p_i is the momentum, m_i the mass and N_f the color factor of fermion f_i, and $A_i^0(s)$ is given by :

$$A_i^0(s) = |A_{iL}(s)|^2 + |A_{iR}(s)|^2$$

$$A_{iL,R}(s) = Q_i + \frac{2cos2\theta_W}{sin^2 2\theta_W}(T_{3i} - Q_i sin^2\theta_W)BW_Z$$

with :

$$BW_Z = \frac{s}{s - M_Z^2 + i\sqrt{s}\Gamma_Z}$$

Similarly, one has :

$$\Gamma(\omega_T \to \bar{f}_i f_i) = \frac{N_f \alpha^2}{3\alpha_{\rho_T}} \frac{p_i(s+2m_i^2)}{s} B_i^0(s)$$

$$B_i^0(s) = (|B_{iL}(s)|^2 + |B_{iR}(s)|^2)(Q_U + Q_D)^2$$

$$B_{iL,R}(s) = Q_i - \frac{4sin^2\theta_W}{sin^2 2\theta_W}(T_{3i} - Q_i sin^2\theta_W)BW_Z$$

where Q_U and $Q_D = Q_U - 1$ are the electric charges of the technifermions which form the ω_T. One assumes Q_U=4/3 in [12].

$\alpha_{\rho_T} \sim 8.73/N_{TC}$ is obtained by naive scaling from the QCD coupling for $\rho \to \pi\pi$. N$_{TC}$ is the dimension of the TC gauge group SU(N$_{TC}$) and N$_{TC}$=4 is assumed as in [6].

Coupling of technivector mesons to technipions

Whenever kinematically possible, ρ_T decays into technipions (or longitudinal W) in a dominant way. In the formula given in section 4.1 the ρ propagator has been chosen such that it remains finite when the ρ mass becomes very large.

The angular distribution of the decay of ρ_T^0 into technipions (or longitudinally polarised W) goes like :

$$\frac{d\sigma}{dcos\theta_\pi} \sim sin^2\theta_\pi$$

while the standard process $e^-e^+ \to W^-W^+$ is forward peaked (neutrino exchange term) in cosθ_{W^-}. If one can identify the sign of the W, as in the semi-leptonic analysis, one can therefore separate the two processes efficiently.

Coupling of technipions to fermions

From [12], one has :

$$\Gamma(\pi_T \to \bar{f}' f) = \frac{N_D^2}{F_\pi^2} N_f p_f C_{ff'}^2 (m_f + m_{f'})^2$$

where $F_\pi \sim 250$ GeV is the EW scale, and $C_{ff'}$ is a model dependent factor. In ref [12] this factor is taken to be of order one, implying a predominant decay into b-quarks. In [16], the technipions are assumed to follow the same pattern as the W, i.e. C_{cb} is of order V_{cb}, implying that the charged technipions decay predominantly into $c\bar{s}$ and $\tau\nu$. In the latter case one can directly derive limits on $\pi_T^+\pi_T^-$ from the standard searches on charged Higgs pairs[17] meaning that $M_{\pi_T^+}$ >77.3 GeV for a heavy ρ_T, since in this case the cross section for H^+H^- is almost equal to $\pi_T\pi_T$. This result is only true if there is no mixing. If there is maximal mixing, as is the case for N_D=2, the $\pi_T^+\pi_T^-$ cross-section decreases by a factor 4. One can still recover a similar limit assuming the ρ_T is light, explicitly with M_{ρ_T} <270 GeV.

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